$\boxed{5.23}$ sample 1 : $N_d = 5\times10^{16}\,cm^{-3}$ As

sample 2 : $N_a = 2\times10^{16}\,cm^{-3}$ B

sample 3 : $N_d = 5\times10^{16}\,cm^{-3}$ As
$N_a = 2\times10^{16}\,cm^{-3}$ B

a) Find n_i in each sample

1. $n_0 \approx N_d = \boxed{5\times10^{16}\,cm^{-3}}$

$p_0 = n_i^2/n_0 = (1.5\times10^{10}\,cm^{-3})^2/5\times10^{16}\,cm^{-3} = \boxed{4.5\times10^{3}\,cm^{-3}}$

2. $p_0 \approx N_a = \boxed{2\times10^{16}\,cm^{-3}}$

$n_0 = n_i^2/p_0 = (1.5\times10^{10}\,cm^{-3})/2\times10^{16}\,cm^{-3} \boxed{= 1.13\times10^{4}\,cm^{-3}}$

3. Since $N_d - N_a = 3\times10^{16}\,cm^{-3} >> n_i$

$n_0 \approx N_d - N_a = \boxed{3\times10^{16}\,cm^{-3}}$

$p_0 = n_i^2/n_0 = (1.5\times10^{10}\,cm^{-3})/(3\times10^{16}\,cm^{-3}) \boxed{= 7.5\times10^{3}\,cm^{-3}}$

b) Determine majority carrier mobility

From Fig 5.3 :
1. $\mu_n \approx 1100\,cm^2/V\cdot s$
2. $\mu_p \approx 400\,cm^2/V\cdot s$
3. $\mu_n \approx 1000\,cm^2/V\cdot s$

c) $\sigma = e(\mu_n n + \mu_p p)$

1. $\sigma \approx e\mu_n n = (1.6\times10^{-19}\,c)(1100\,cm^2/V\cdot s)(5\times10^{16}\,cm^{-3}) \boxed{= 8.8\,[\Omega\text{-}cm]^{-1}}$

2. $\sigma \approx e\mu_p p = (1.6\times10^{-19}\,c)(400\,cm^2/V\cdot s)(2\times10^{16}\,cm^{-3}) \boxed{= 1.28\,[\Omega\text{-}cm]^{-1}}$

3. $\sigma \approx e\mu_n n = (1.6\times10^{-19}\,c)(1000\,cm^2/V\cdot s)(3\times10^{16}\,cm^{-3}) \boxed{= 4.8\,[\Omega\text{-}cm]^{-1}}$

d) $J_{drf} = e(\mu_n n + \mu_p p)E = (\sigma_n + \sigma_p)E$

1. $E = \dfrac{J_{drf}}{\sigma_n} = \dfrac{120\,A/cm^2}{8.8\,[\Omega\text{-}cm]^{-1}} = \boxed{13.64\,V/cm}$

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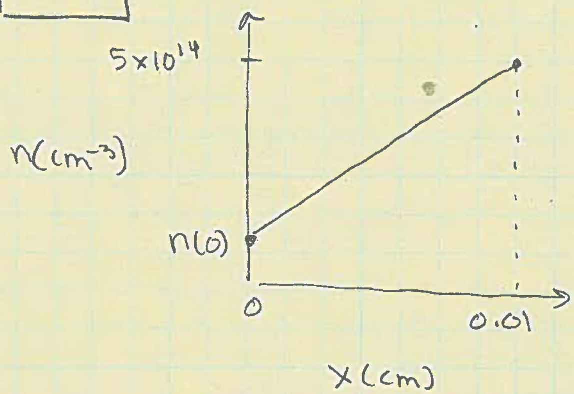
2. $E = \frac{J_{drf}}{\sigma_p} = \frac{120\ A/cm^2}{1.28\ [\Omega\text{-}cm]^{-1}} \boxed{= 93.75\ V/cm}$

3. $E = \frac{J_{drf}}{\sigma_{n_3}} = \frac{120\ A/cm^2}{4.8\ [\Omega\text{-}cm]^{-1}} = \boxed{25.0\ V/cm}$

5.29 Si @ T = 300 K



$J_n|_{diff} = 0.19\ A/cm^2$

$D_n = 25\ cm^2/s$

What is $n(0)$?

$$J_{n\,diff} = eD_n \frac{dn}{dx} \approx eD_n \frac{\Delta n}{\Delta x} = \frac{eD_n(5\times10^{14}cm^{-3} - n(0))}{\Delta x}$$

$$n(0) = 5\times10^{14}\ cm^{-3} - \frac{J_{n\,diff}\cdot\Delta x}{eD_n}$$

$$= 5\times10^{14}\ cm^{-3} - \frac{(0.19\ A/cm^2)(0.01\ cm)}{(1.6\times10^{-19}c)(25\ cm^2/s)} \boxed{= 2.5\times10^{13}\ cm^{-3}}$$

5.35 Si @ T = 300 K

$n(x) = 10^{16}\exp\left[\frac{-x}{18}\right]\ [cm^{-3}]$ x is in um

$0 \le x \le 25\,um$

$D_n = 25\ cm^2/s$

$\mu_n = 960\ cm^2/V\cdot s$

$J_n = -40\ A/cm^2$ total electron current density (drift + diff)

$$J_n = en\mu_n E + eD_n\frac{dn}{dx} = -40\ A/cm^2$$

$$\frac{dn}{dx} = -10^{16}[cm^{-3}]\exp\left[-\frac{x}{18}\right]\cdot\frac{1}{18\,[um]}$$

$$J_n = en\mu_n E - \frac{eD_n\,10^{16}[cm^{-3}]}{18\,[um]}\exp\left[\frac{-x}{18}\right] = -40\ A/cm^2$$

so $E = \dfrac{-40\ A/cm^2 + \dfrac{eD_n 10^{16} [cm^{-3}]}{18 [um]} \exp\left[\dfrac{-x}{18}\right]}{e\mu_n 10^{16} \exp\left[\dfrac{-x}{18}\right]}$

$$E = \frac{-40\ A/cm^2 + \dfrac{0.04\ A/cm}{18\times10^{-4}\ cm} \exp\left[\dfrac{-x}{18}\right]}{1.536\ \dfrac{c\cdot cm^2}{V\cdot s}\cdot\dfrac{1}{cm^3} \exp\left[\dfrac{-x}{18}\right]}$$

$$E(x) = \frac{22.22\ A/cm^2 \exp\left[\dfrac{-x}{18}\right] - 40\ A/cm^2}{1.536\ \dfrac{A}{V\cdot cm} \exp\left[\dfrac{-x}{18}\right]}$$

$$\boxed{E(x) = 14.47 - 26.04 \exp\left[\frac{x}{18}\right] \quad [V/cm]}$$

$\boxed{5.36}$

$J = -10\ A/cm^2 \longrightarrow \overset{\text{hole}}{\text{drift}} + \overset{\text{electron}}{\text{diffusion}}$

$p_o = 10^{16}\ cm^{-3}$

$n(x) = 2\times10^{15}\ e^{-x/L}\ cm^{-3}$, $L = 15\ um$

$D_n = 27\ cm^2/s$, $\mu_p = 420\ cm^2/V\cdot s$

a) Find $J_{n|diff}$ for $x > 0$

$$J_{n|diff} = eD_n \frac{dn}{dx} = -\frac{eD_n}{L(um)}(2\times10^{15})\ e^{-x/L}$$

$$= -\frac{(1.6\times10^{-19}\ c)(27\ cm^2/s)}{(15\times10^{-4}\ cm)}(2\times10^{15}\ cm^{-3})\ e^{-x/L}$$

$$\boxed{J_{n|diff} = -5.76\ e^{-x/15um}} \quad [A/cm^2]$$

b) $J_{p|drf} = e\mu_p p E = (1.6\times10^{-19}\ c)(420\ cm^2/V\cdot s)(10^{16}\ cm^{-3})\ E$

$$J_{p|drf} = 0.672\ E$$

c) $J_{TOT} = J_{n|diff} + J_{p|drf}$

$$-10\ A/cm^2 = -5.76\ e^{-x/15um} + 0.672\ E$$

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- so $E = \dfrac{5.76\, e^{-x/15\mu m} - 10}{0.672}$

$$\boxed{E(x) = 8.57 e^{-x/15} - 14.9 \quad [V/cm]}$$

5.40 n-type $T = 300K$ $J = 0$

$N_d(x) = N_{do}\, e^{-x/L}$ From $0 \le x \le L$

$N_{do} = 10^{16}\ cm^{-3}$

$L = 10\ \mu m$

a) What is $E(x)$? For no current, drift must equal diffusion

so $e n \mu_n E_x = -e D_n \dfrac{dn}{dx}$

$n E_x = \dfrac{D_n}{\mu_n} \dfrac{dn}{dx}$ and $\dfrac{D_n}{\mu_n} = \dfrac{kT}{e}$

so $E_x = -\dfrac{kT}{e} \dfrac{1}{n} \dfrac{dn}{dx}$

$$E_x = -\frac{kT}{e} \frac{1}{N_{do}} e^{x/L} \cdot \left(-\frac{N_{do}}{L} e^{-x/L}\right) = \frac{kT}{e} \cdot \frac{1}{L}$$

$$E_x = (0.0259V) \cdot \frac{1}{10 \times 10^{-4}\ cm} = \boxed{25.9\ V/cm}$$

b) Calculate potential difference between $x=0$ and $x=L$

higher lower

$$\phi = -\int_0^L E(x)\, dx = -EL - E \cdot 0$$

$$= -EL = (-25.9 V/cm)(10 \times 10^{-4}\ cm) = \boxed{-0.0259V}$$

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$\boxed{5.45}$ $T = 300\ K$

a) $\mu_n = 1150\ cm^2/V \cdot s$

$\mu_n = 6200\ cm^2/V \cdot s$

use Einstein relation $\frac{D_n}{\mu_n} = \frac{kT}{e} \Rightarrow D_n = \mu_n \frac{kT}{e}$

(i) $D_n = (1150\ cm^2/V \cdot s)(0.0259\ V) = \boxed{29.8\ cm^2/s}$

(ii) $D_n = (6200\ cm^2/V \cdot s)(0.0259 V) = \boxed{160.6\ cm^2/s}$

b) (i) $D_p = 8\ cm^2/s \Longrightarrow \mu_p = \frac{D_p}{(kT/e)} = \frac{8\ cm^2/s}{0.0259 V} = \boxed{308.9\ cm^2/V \cdot s}$

(ii) $D_p = 35\ cm^2/s$

$\Longrightarrow \mu_p = \frac{35\ cm^2/s}{0.0259\ V} = \boxed{1351.4\ cm^2/V \cdot s}$

$\boxed{7.4}$ Si pn junction $N_a = 10^{17}\ cm^{-3}$, $N_d = 5 \times 10^{15}\ cm^{-3}$

$T = 300\ K$

a) Find $E_F - E_{Fi}$ on both sides of junction

$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \Rightarrow E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)$

assuming 100% ionization $E_F - E_{Fi} = kT \ln\left(\frac{N_d}{n_i}\right)$

so $E_F - E_{Fi} = (0.0259 eV) \ln\left(\frac{5 \times 10^{15} cm^{-3}}{1.5 \times 10^{10} cm^{-3}}\right) = \boxed{0.329 eV}$

For p-side $E_F - E_{Fi} = -kT \ln\left(\frac{N_a}{n_i}\right)$

$E_F - E_{Fi} = -(0.0259 eV) \ln\left(\frac{10^{17} cm^{-3}}{1.5 \times 10^{10} cm^{-3}}\right) = \boxed{-0.407 eV}$

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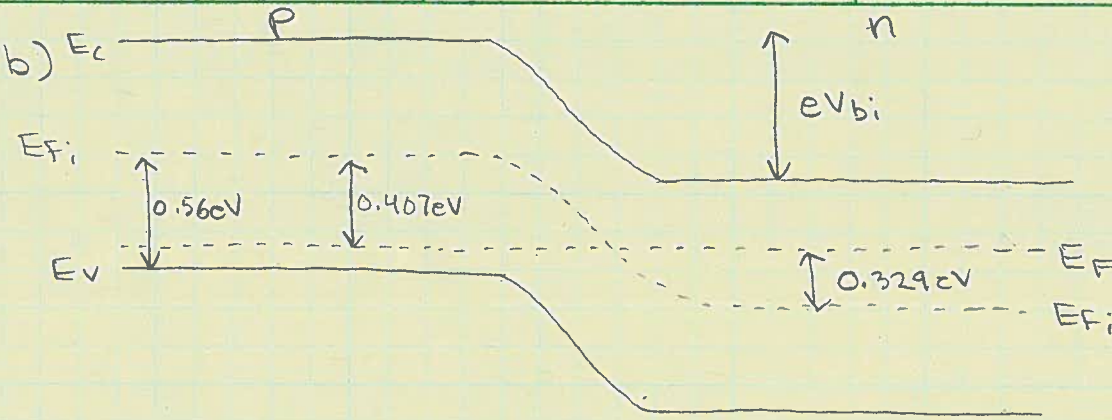
b)



$$eV_{bi} = (E_{Fi} - E_v)_p + (E_F - E_{Fi})_n$$

so $eV_{bi} = 0.407\text{eV} + 0.329\text{eV} = 0.736\text{eV}$

$$\Longrightarrow \boxed{V_{bi} = 0.736\text{ V}}$$

c) $V_{bi} = \frac{kT}{e} \ln\left(\frac{N_d \cdot N_a}{n_i^2}\right)$

$$= (0.0259\text{V}) \ln\left(\frac{(5\times10^{15}\text{cm}^{-3})(1\times10^{17}\text{cm}^{-3})}{(1.5\times10^{10})^2}\right) \boxed{= 0.736\text{ V}}$$

same as part (b)

d) Find x_n, x_p, and $|E_{max}|$

$$x_n = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

$$x_n = \left\{\frac{2(11.7)(8.85\times10^{-14}\text{F/cm})(0.736\text{V})}{(1.6\times10^{-19}\text{c})} \frac{1\times10^{17}\text{cm}^{-3}}{5\times10^{15}\text{cm}^{-3}} \frac{1}{1\times10^{17}\text{cm}^{-3} + 5\times10^{15}\text{cm}^{-3}}\right\}^{1/2}$$

$$= 4.26\times10^{-5}\text{ cm} = \boxed{0.426\text{ um}}$$

For x_p: $N_a x_p = N_d x_n \Longrightarrow x_p = \frac{(5\times10^{15}\text{cm}^{-3})}{(1\times10^{17}\text{cm}^{-3})}(0.426\text{um})$

$$\boxed{x_p = 0.0213\text{ um}}$$

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$$|E_{max}| = \left| -\frac{eN_d}{\epsilon_s} x_n \right|$$

$$= \frac{(1.6\times10^{-19}\,C)(5\times10^{15}\,cm^{-3})(0.426\times10^{-4}\,cm)}{(11.7)(8.85\times10^{-14}\,F/cm)}$$

$$\boxed{|E_{max}| = 3.29\times10^{4}\ V/cm}$$

7.8 (a) Si pn junction $T = 300\,K$

at $V=0$, 25% of space charge is in the n-region

$V_{bi} = 0.710\ V$

(i) N_a? $x_n = 0.25W$ $x_p = 0.75W$

$$\Rightarrow x_n = \frac{0.25}{0.75} x_p$$

$$\text{so } N_d x_n = \frac{N_d x_p}{3} = N_a x_p$$

$$\Rightarrow N_d = 3N_a$$

$$\text{so } V_{bi} = \frac{kT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right) = \frac{kT}{e}\ln\left(\frac{3N_a^2}{n_i^2}\right) = \frac{2kT}{e}\ln\left(\frac{\sqrt{3}N_a}{n_i}\right)$$

$$N_a = \frac{n_i}{\sqrt{3}}\exp\left[\frac{V_{bi}}{(2kT/e)}\right] = \frac{1.5\times10^{10}\,cm^{-3}}{\sqrt{3}}\exp\left[\frac{0.710\,V}{2(0.0259\,V)}\right]$$

$$\boxed{N_a = 7.77\times10^{15}\,cm^{-3}}$$

(ii)

$$\boxed{N_d = 3N_a = 2.33\times10^{16}\,cm^{-3}}$$

(iii)

$$x_n = \left\{\frac{2(11.7)(8.85\times10^{-14}\,F/cm)(0.71)}{1.6\times10^{-19}}\left[\frac{1}{3}\right]\left[\frac{1}{7.77\times10^{15}\,cm^{-3}+2.33\times10^{16}\,cm^{-3}}\right]\right\}^{1/2}$$

$$\boxed{x_n = 0.0993\,\mu m}$$

(iv)

$$\text{so } x_p = x_n\frac{N_d}{N_a} = x_n\cdot 3 = \boxed{0.298\,\mu m}$$

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(v) $|E_{max}| = \dfrac{eN_d x_n}{\epsilon_s}$

$= \dfrac{(1.6\times10^{-19}c)(2.33\times10^{16}cm^{-3})(0.0993um)}{(11.7)(8.85\times10^{-14}F/cm)}$ $\boxed{= 3.58\times10^{4}\ V/cm}$

(b) Same as part (a) but use $n_i = 1.8\times10^{6}\ cm^{-3}$

Process is same as (a)

(i) $N_a = 8.13\times10^{15}\ cm^{-3}$

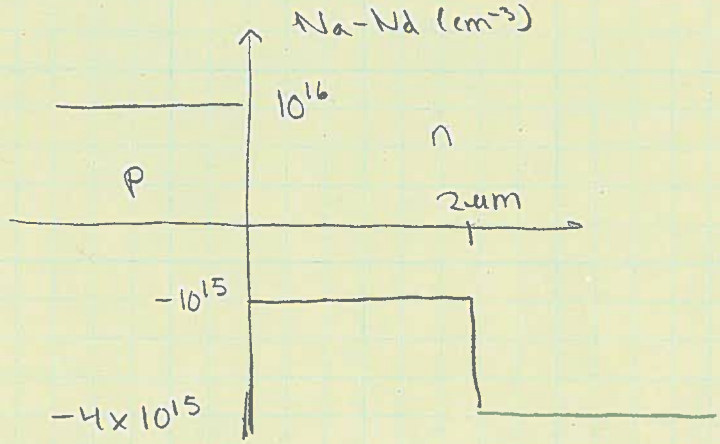
(ii) $N_d = 2.44\times10^{16}\ cm^{-3}$

(iii) $x_n = 0.1324\ um$

(iv) $x_p = 0.397\ um$

(v) $|E_{max}| = 4.45\times10^{4}\ V/cm$

7.9



Silicon

assume T=300K

* assume $x_n < 2um$ ⟹ V_{bi} is same as normal step junction

a) $V_{bi} = \dfrac{kT}{e}\ln\left(\dfrac{N_d N_a}{n_i^2}\right) = 0.0259V\ln\left(\dfrac{10^{15}\cdot10^{16}}{(1.5\times10^{10})^2}\right) = 0.635\ V$

b) $x_n = \left\{\dfrac{2\epsilon_s V_{bi}}{e}\left[\dfrac{N_a}{N_d}\right]\left[\dfrac{1}{N_a+N_d}\right]\right\}^{1/2}$

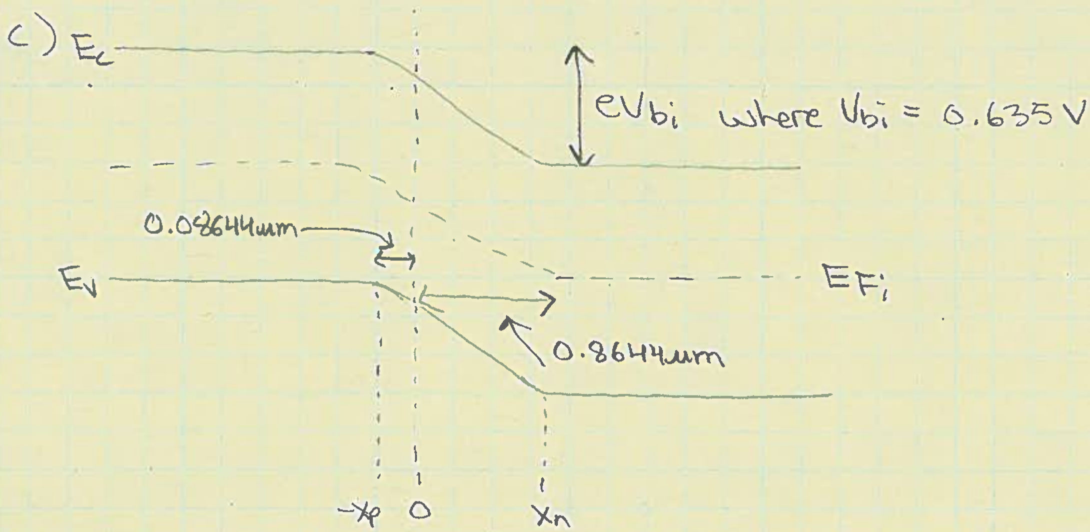
$x_n = \left\{\dfrac{(2)(11.7)(8.85\times10^{-14}F/cm)(0.635V)}{(1.6\times10^{-19}c)}\left[\dfrac{1\times10^{16}\ cm^{-3}}{1\times10^{15}\ cm^{-3}}\right]\left[\dfrac{1}{1\times10^{16}cm^{-3}+1\times10^{15}cm^{-3}}\right]\right\}^{1/2}$

$x_n = 0.8644 \times 10^{-4}$ cm $\boxed{= 0.8644\,\mu m}$

$N_d x_n = N_a x_p \implies x_p = \dfrac{N_d}{N_a} x_n$

$x_p = \dfrac{(1 \times 10^{15}\,cm^{-3})}{(1 \times 10^{16}\,cm^{-3})}(0.8644\,\mu m) = \boxed{0.08644\,\mu m}$

c)



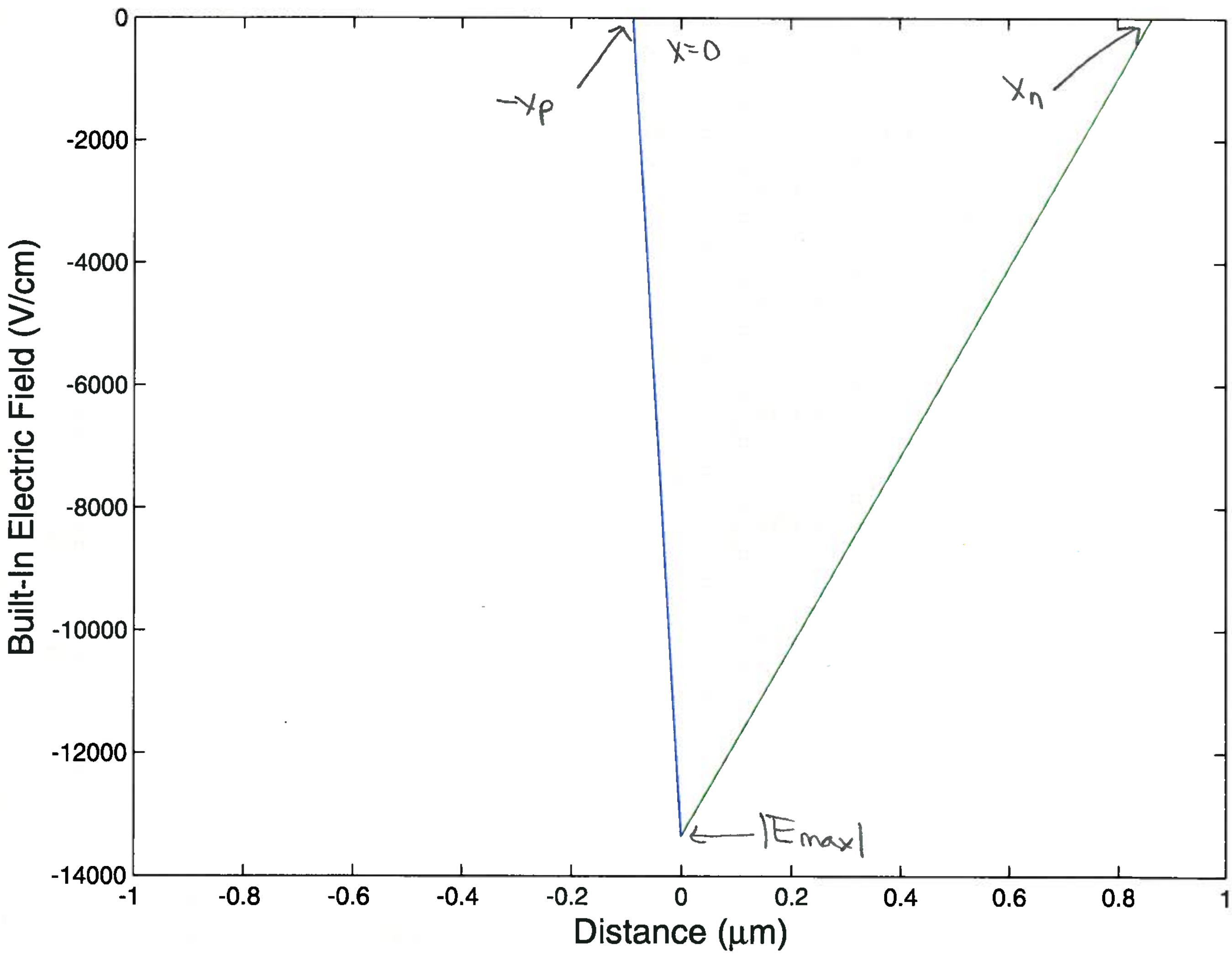
d) Find $|E_{max}|$: $\quad |E_{max}| = \dfrac{e N_d x_n}{\epsilon_s}$

$|E_{max}| = \dfrac{(1.6 \times 10^{-19} C)(10^{15} cm^{-3})(0.8644 \times 10^{-4} cm)}{(11.7)(8.85 \times 10^{-14} F/cm)} = \boxed{1.34 \times 10^{4}\ V/cm}$

on the p-side: $E_p(x) = \dfrac{-e N_a}{\epsilon_s}(x + x_p)$ From $-x_p \le x \le 0$

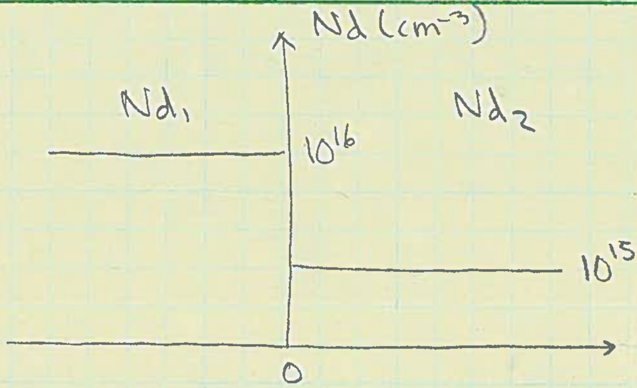
on the n-side: $E_n(x) = \dfrac{-e N_d}{\epsilon_s}(x_n - x)$ From $0 \le x \le x_n$

<u>SEE MATLAB PLOT</u>



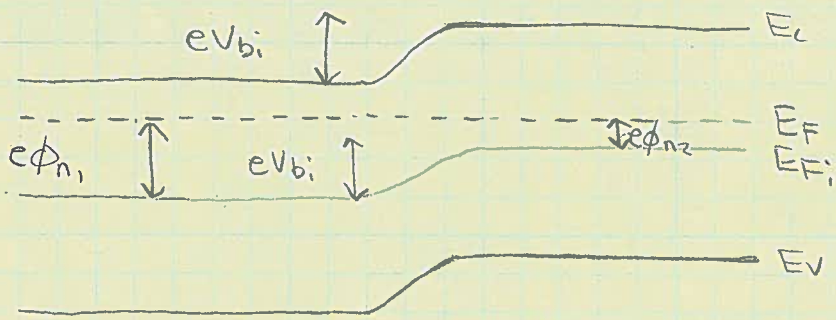
Built-In Electric Field (V/cm)
Distance (μm)
0
-2000
-4000
-6000
-8000
-10000
-12000
-14000
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$-x_p$
$x=0$
x_n
$|E_{max}|$

$\boxed{7.12}$



* assume the material is silicon

(a) Fermi level is constant



$e\phi_{n_1} = (E_F - E_{Fi})_1 \qquad \phi_{n_2} = (E_F - E_{Fi})_2$

$eV_{bi} = \phi_{n_1} - \phi_{n_2}$

For n-type: $n_0 \approx N_d = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$

$\Rightarrow E_F - E_{Fi} = kT \ln\left(\frac{N_d}{n_i}\right)$

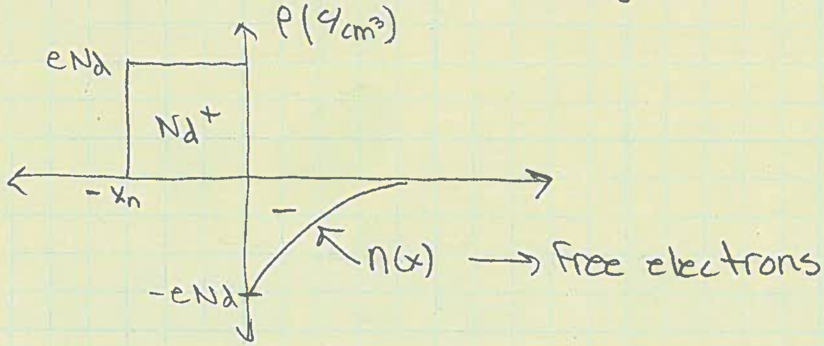
For N_{d1}: $(E_F - E_{Fi})_1 = 0.0259\,eV \ln\left(\frac{10^{16}\,cm^{-3}}{1.5\times10^{10}\,cm^{-3}}\right) = 0.3473\,eV$

For N_{d2}: $(E_F - E_{Fi})_2 = 0.0259\,eV \ln\left(\frac{10^{15}\,cm^{-3}}{1.5\times10^{10}\,cm^{-3}}\right) = 0.2877\,eV$

so $eV_{bi} = 0.3473\,eV - 0.2877\,eV = 0.0596\,eV$

$\Rightarrow \boxed{V_{bi} = 0.0596\,V}$

c) Electrons will diffuse from the side with higher doping to the side with lower doping. A depletion region will be left on the highly doped side and free electrons will diffuse to the lowly doped side. This occurs since the Fermi level must be constant throughout the junction



$E \longrightarrow$ Eletric field still sets up to balance the diffusion

$$\rho(x) = \begin{cases} eN_d & -x_n \leq x \leq 0 \\ -en(x) & x \geq 0 \end{cases}$$